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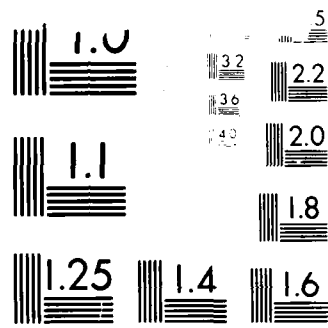
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INVENTORY SYSTEM

April 1986

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Summary

LATERAL RESUPPLY IN A MULTI-ECHELON INVENTORY SYSTEM

We model a multi-echelon ($s-1,s$) continuous review, resupply system in which inter-site movement of assets within the same echelon (lateral resupplies) are permitted. Lateral resupply – the lateral movement of assets within a given supply echelon from one site to another to satisfy supply shortages – is common in large, multi-echelon supply systems. In fiscal year 1985, for example, approximately 8 percent of supply shortages affecting aircraft mission capability in the U.S. Air Force were satisfied by lateral resupply between bases.

Existing methods for modeling lateral resupply are not practical for use in large-scale models such as the Air Force METRIC (Multi-Echelon Technique for Recoverable Item Control) model [1]. We modify the METRIC approach, which computes total retail expected backorders by item from standard logistics input data (e.g., failure rates and wholesale and retail repair and resupply times), to include incorporation of lateral resupply in the system. Described in terms of a one-item model, our method is specifically designed to provide for efficient processing in a multi-item model.

Incorporation of this method in Air Force METRIC-based models can improve evaluation of supply system effects on peacetime readiness and wartime sustainability.

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LATERAL RESUPPLY IN A MULTI-ECHELON INVENTORY SYSTEM

BACKGROUND

The goal of any inventory system is to maximize customer support with a minimum of inventory. A two-echelon inventory system is designed to better support retail customers by adding, to the retail stockage locations, a central wholesale depot. By providing some support at the retail echelon, and greater range and depth at wholesale, the system strikes a balance between the quick response of decentralized stock and the economies of scale of centralized stock. If the system involves recoverable items, the repair capabilities of the echelons may mirror their stockage policies, the higher echelon (the depot) having the greater repair capability.

Such a structure typifies many logistics supply systems; the U.S. Air Force (USAF) is a prime example. Models of such large multi-echelon inventory systems have been based traditionally on Sherbrooke's METRIC [1] model or on similar mathematics. These models treat the system as a strict arborescence, which, in the two-echelon case, permits shipments between a retail site and the depot only.

Yet, shipments between retail sites are frequent in two-echelon logistics systems. By permitting such "lateral resupplies," the system enables retail stocks to act as central stocks as well. For example, lateral resupplies between Air Force bases in Europe are so common that the Air Force has developed the European Distribution System, which is dedicated to such activity. In fact, during fiscal year 1985, approximately 8 percent of USAF supply shortages affecting aircraft mission capability were satisfied by lateral resupply. But models based on METRIC are not structured to handle lateral resupply. METRIC's retail computations view each site as independent of the other sites in the same echelon.

Many non-METRIC-based models incorporate lateral resupply, but they take a more detailed view of the flows of spares in the system than is practical for large-scale modeling [2,3]. The reason

for METRIC's wide application is its structural simplicity, which works with "pipelines" of spares in various forms of resupply. We present here a model that is similar to METRIC in structure but with explicit consideration of lateral resupply.

APPROACH

We model a two-echelon $(s-1, s)$, continuous review, resupply system with one depot and a number of identical retail sites (bases) that practice lateral resupply. Demands at each base are generated by a Poisson process. When a demand arrives at a base, either it is filled immediately (if there is a spare on hand at that base) or it is backordered. Accompanying the demand is a failed component (or carcass) that the customer turns in to base supply. If the carcass is base-repairable, it is inducted into base repair; if not, it is returned to the depot for repair or condemnation.

If the demand is filled immediately, the resupply system operates as it would if lateral resupply were prohibited. If the carcass is not base repairable, a replacement is ordered from the depot.

If the demand is backordered, base supply looks for the fastest way to fill the order. If there are units in base repair, even the unit that has just been turned in, that is often the fastest source of resupply; if not, or if a delay in repair is expected, base supply checks to see whether another base can fill the order. If another base has a spare, that base ships it to the first base, thereby terminating the backorder. If no other base has a spare, the first base must wait for base repair or resupply from the depot.

After a lateral resupply, the first base "owes" the supplying base a spare. Typically, the carcass is not base-repairable, and the supplying base (in lieu of the first base) orders the replacement from the depot, thereby canceling the debt. If the carcass is base-repairable, the debt may be canceled via another lateral resupply when the first base obtains a spare to ship (via any means). This occurs rarely and is the only time when a lateral resupply is not used to terminate a backorder.

ESTIMATION OF TOTAL BASE EXPECTED BACKORDERS UNDER LATERAL RESUPPLY

Our objective is to compute the total number of expected backorders at the bases. The procedure is to calculate the expected number of spares in lateral resupply (in transit between bases)

under some simplifying assumptions. This provides an estimate of the expected backorders at the bases; this estimate is then made more precise by dropping the simplifying assumptions.

We use lower-case letters to signify the variables for each base:

b_n = expected backorders at Base n when there is lateral resupply between bases

s_n = stock level at Base n

x_n = number of units in resupply to Base n (due in from the depot or from other bases).

We make use of a perspective where the entire retail echelon is viewed as a single dispersed base. We are concerned with the status of the echelon as a whole (i.e., what the asset position is, whether there are any spares available, etc.) from this point of view. Upper-case letters represent the variables for the echelon as a single base:

B = expected backorders for the echelon as a single base

S = stock level for the echelon as a single base

X = number of units in resupply to the echelon as a single base (from the depot).

Because of lateral resupply, an upper-case variable is not always the sum of its lower-case counterparts:

$$S = \sum s_n \quad (1)$$

$$X \leq \sum x_n \quad (2)$$

where $(s - x) > 0$ is the number of units of stock on hand and $(x - s) > 0$ is the number of backorders. Since the probabilities for $X, p(X)$, are known, we can calculate B from steady-state inventory theory and Palm's theorem:

$$B = \sum (X - S) p(X) \quad (3)$$

and we assert that:

$$\sum b_n = B + P \quad (4)$$

where P is the expected number of units in the lateral resupply pipeline between bases, provided that the following simplifying assumptions hold:

- (1) *Spares in transit from the depot to bases can be rerouted to arrive at any base without additional delay.*
- (2) *A resupply from the depot will never terminate or pre-empt a lateral resupply.* If a unit in transit from the depot to a base arrives while a lateral resupply is also in transit to that base, the unit from the depot can be used to terminate the backorder. For now, we assume that either this never happens or the backorder is forced to wait for the lateral resupply.
- (3) *There is no base repair.* This, in combination with the first assumption, means that a spare never shows up at the wrong base. Bases that have backorders take precedence over bases that do not, and always receive spares first.

Proof: A lateral resupply is made if, and only if, there is stock at the echelon as a single base, and a backorder exists at an individual base. Since we have assumed for simplicity that, in this situation, a backorder at a base is never terminated by a depot shipment, there is a one-to-one correspondence between spares in the lateral resupply pipeline and those backorders that would not exist for the echelon as a single base.

COMPUTATION OF THE LATERAL RESUPPLY PIPELINE

We now describe a procedure for estimating P , the lateral resupply pipeline. Note that, since the bases are identical, all the demand rates, average resupply times, etc., are the same for all bases.

Let:

- M = mean demand rate for the echelon as a single base
- T = lateral resupply time between any two bases
- F = fill rate for the echelon as a single base
- f = fill rate for each base ($= f_n$ for any n).

Then we assert that:

$$P = MT(F - f) \quad (5)$$

Proof: A lateral resupply occurs when there is a fill for the echelon (as a single base), but no fill at the individual base where the demand occurred. The average number in the lateral resupply pipeline is this fraction multiplied by the demand rate and the average lateral resupply time.

ESTIMATION OF BASE FILL RATE UNDER LATERAL RESUPPLY

In equation (5), M and T are known constants, and the fill rate for the echelon, F , is easy to compute from steady-state theory. We need only estimate f to estimate P and then Σb_n in equation (4).

A customer who must wait for a lateral resupply is not counted as a fill, regardless of the length of that wait. Furthermore, because of the one-to-one correspondence between units in lateral resupply and backordered customers waiting for those units, the lateral resupply time affects only these customers. Therefore, the fill rate is not a function of the lateral supply time. Thus, we may consider the limiting case as the lateral resupply time is reduced to zero, computing f when there are no units in the lateral supply pipeline. Equation (2) now becomes an equality:

$$X = \sum x_n \quad (6)$$

Without loss of generality, we compute f as the probability that a demand at a random point in time at Base 1 is filled instantly. This is the probability that $(s_1 - x_1)$ is greater than zero. But, in the limiting case, as L approaches zero, $(s_1 - x_1)$ cannot be greater than zero while some other $(s_n - x_n)$ is less than zero, because such a situation would immediately trigger a lateral resupply to the other base. Therefore, the probability that $(s_1 - x_1)$ is greater than zero equals the probability that $(S - X)$ is greater than zero; that is, that there are units of stock on hand in the echelon, and that one of those on-hand units is at Base 1. Then, the fill rate is given by:

$$f = F - P_1 \quad (7)$$

where P_1 is the probability that the echelon has on-hand units, but none of them are at Base 1. Or, more specifically

$$\begin{aligned}
 P_1 = & p[(S - X) = 1] \cdot p[\text{the on-hand spare is not at Base 1}] \\
 & + P[(S - X) = 2] \cdot p[\text{neither of the on-hand spares is at Base 1}] \\
 & + p[(S - X) = 3] \cdot p[\text{none of the on-hand spares are at Base 1}] \\
 & + \dots
 \end{aligned}
 \tag{8}$$

The first term above, the probability that there is one spares on hand in the echelon (but not at Base 1), is given by $p[(S - X) = 1](N - 1)/N$, where N is the number of bases. The succeeding terms, the probability of 1 spares on hand in the echelon but none at Base 1, may be bounded by considering how spares may be distributed throughout the echelon. If we make the optimistic assumption that the on-hand spares are distributed as uniformly as possible among the bases (i.e., no base may have two on-hand spares if another base has none), we get:

$$f = F - \sum_{i=1}^{N-1} p[(S - X) = i] \cdot \frac{N-i}{N}
 \tag{9}$$

Note that if the inventory position at each base is 1, the above formula gives the actual fill rate because two on-hand spares at the same base would be impossible. If we make the pessimistic assumption of a random distribution of on-hand spares across the bases, we get:

$$f = F - \sum_{i=1}^{S-s} p[(S - X) = i] \cdot \left(\frac{N-1}{N} \right)^i
 \tag{10}$$

where s equal s_n , for any n , because of the uniform-base assumption.

These two formulas [equations (9) and (10)] are the upper and lower bounds for fill rate. In practice, the distribution of spares will be neither maximally uniform nor completely random. Thus, the true fill rate must lie somewhere between these two extremes. Further study, possibly involving simulations is needed to refine these bounds.

Thus, using equations (4) and (5) and either (9) or (10), we can estimate the total expected backorders at all the bases. In limited investigations thus far, the optimistic and pessimistic assumptions have yielded similar results. One typical three-base case with an expected backorder level for the echelon as a single base of 0.96 gave lateral resupply pipelines of 0.15 and 0.20 for the optimistic and pessimistic assumptions, respectively.

We now eliminate our temporary assumptions, one at a time. We begin by dropping assumption 1 (about rerouting in transits from the depot), followed by assumption 2 (about pre-empting lateral resupplies). Last, we drop the assumption that prohibits base repair.

THE DELAYED LATERAL RESUPPLY PIPELINE

The first of the three temporary assumptions used in the derivation stated that depot shipments could be rerouted in transit. This is impossible in practice: Units being shipped from the depot arrive where they are headed, not necessarily where they are needed.

The lateral resupply pipeline in equation (4) represents the "instantaneous" lateral resupply pipeline where lateral resupply is initiated immediately following a demand. We must also compute a "delayed" lateral resupply pipeline that represents lateral resupplies that occur when the echelon cannot fill an order when it is received, and a unit in the order-and-ship pipeline is used to satisfy the demand on arrival.

As before, let X represent the number of units in resupply and S the total echelon spares level. Also, let D denote the number of spares, either in transit to the depot or in depot repair. Then, $X - D$ is the number of units in transit from the depot. A delayed lateral supply to a given base—say, Base 1—occurs if, at the time of the demand, the whole echelon (including Base 1) is out of stock ($S \leq X$), but enough spares are in transit from the depot to cover all outstanding backorders plus this latest demand; i.e., $X - D \geq (X - S) + 1$, unless:

- (1) The spare that was the candidate for lateral shipment arrives at Base 1, thereby satisfying the demand without a lateral resupply, or
- (2) The candidate spare arrives at Base n , $n \neq 1$, but is pre-empted by another demand occurring at Base n after the customer's demand but before the candidate spare arrives.

In deriving an expression for the conditional probability of a delayed lateral resupply satisfying a demand, given that the demand cannot be immediately so satisfied, we use the optimistic assumption about the distribution of spares in the echelon, as discussed previously. This is appropriate here because we are counting spares in transit from the depot as though they were on-hand, which makes the distribution of spares between the bases less random.

Suppose there are enough spares in transit from the depot, i.e., $X - D \geq (X - S) + 1$. The first $X - S$ in-transit spares are used to satisfy backorders that were in place at the time of this latest demand. The remainder, $(X - D) - (X - S) = S - D$, are candidates for a delayed lateral resupply.

Consider the first of these units to arrive. The probability that it arrives at Base n , $n \neq 1$, is $(N - 1)/N$. If we let $p(1)$ denote the probability that this unit is pre-empted by another demand at Base n , the probability that the first candidate triggers a delayed lateral resupply is given by:

$$L(1) = p(S - D > 0 | X \geq S) \cdot \frac{N - 1}{N} \cdot [1 - p(1)] \quad (11)$$

If the first unit is pre-empted, a second candidate may trigger a delayed lateral resupply. The probability of this occurrence is given by:

$$\begin{aligned} L(2) &= p(S - D > 0 | X \geq S) \cdot \frac{N - 1}{N} \cdot p(1) \\ &\quad \cdot p(S - D > 1 | S - D > 0) \cdot \frac{N - 2}{N - 1} \cdot [1 - p(2)] \\ &= p(S - D > 1 | X \geq S) \cdot \frac{N - 2}{N} \cdot p(1) \cdot [1 - p(2)] \end{aligned} \quad (12)$$

where $p(2)$ is the probability the second unit is pre-empted by a demand at the base at which it arrives. Note that our optimistic distribution assumption implies that the probability it arrives at Base n , $n \neq 1$, is given by $(N - 2)/(N - 1)$.

Similarly, if this second unit is pre-empted, the third may trigger a delayed lateral resupply, and so on. The probability that the j^{th} candidate spare triggers a delayed lateral resupply is given by:

$$L(j) = p[S - D > j - 1 | X \geq S] \cdot \frac{N-j}{N} \cdot [p(1)p(2) \dots p(j-1)][1 - p(j)] \quad (13)$$

Then the probability of generating a delayed lateral resupply, given that an instantaneous one did not occur, is given by:

$$L = \sum_{j=1}^{N-1} L(j) \quad (14)$$

$$= \sum_{j=1}^{N-1} p[S - D > j - 1 | X \geq S] \cdot \frac{N-j}{N} \cdot [p(1)p(2) \dots p(j-1)][1 - p(j)] \quad (15)$$

$$= \sum_{j=1}^{N-1} \sum_{d=0}^{S-j} p(D=d | X \geq S) \cdot \frac{N-j}{N} \cdot [p(1)p(2) \dots p(j-1)][1 - p(j)] \quad (16)$$

$$= \frac{1}{p(x \geq S)} \sum_{j=1}^{N-1} \sum_{d=0}^{S-j} p(D=d, X \geq S) \cdot \frac{N-j}{N} \cdot [p(1) \dots p(j-1)][1 - p(j)] \quad (17)$$

$$= \frac{1}{p(x \geq S)} \sum_{j=1}^{N-1} \sum_{d=0}^{S-j} \sum_{x=S}^{\infty} p(D=d, X=x) \cdot \frac{N-j}{N} \cdot [p(1) \dots p(j-1)][1 - p(j)] \quad (18)$$

$$= \frac{1}{p(x \geq S)} \sum_{x=S}^{\infty} \sum_{d=0}^{S-j} \sum_{j=1}^{\alpha} p(D=d, X=x) \cdot \frac{N-j}{N} \cdot [p(1) \dots p(j-1)][1 - p(j)] \quad (19)$$

where $\alpha = \min(N-1, S-D)$.

Since D and X are not independent, we employ the logic of the Simple Simon Model [4] to compute the joint probability, $p(D=d, X=x)$. Let:

t = the point in time for which $p(D=d, X=x)$ is to be computed

T_0 = the depot-to-base order-and-ship time (the time for a demand on the depot to reach a base when the depot is not out of stock)

T_d = the depot resupply time, including the retrograde ship time (the time for a carcass to be restored to serviceable condition, including the time to ship that carcass to the depot)

X_a = the demands made on the depot by the bases in $[t - T_0, t]$

X_b = the demands made on the depot by the bases in $[t - T_d, t - T_0]$

X_c = the demands made on the depot by the bases in $[t - T_d - T_0, t - T_d]$

S_d = the stock level at the depot

Then.

$$D = \max(0, X_a + X_b - S_d) \quad (20)$$

and

$$X = X_a + \max(0, X_b + X_c - S_d) \quad (21)$$

Because X_a , X_b , and X_c are uncorrelated, the probability of a particular (X, D) combination is the product of the probabilities of the X_a , X_b , and X_c , summed over all combinations that give X and D . Let \hat{X} be the vector (X_a, X_b, X_c) and let $\Xi(d, x) = \{\hat{X} | \max(0, X_a + X_b - S_d) = d, X_a + \max(0, X_b + X_c - S_d) = x\}$. Then we can write:

$$p(D=d, X=x) = \sum_{\hat{X} \in \Xi(d, x)} p(X_a)p(X_b)p(X_c) \quad (22)$$

The probability that the j^{th} spare is not pre-empted is the probability of no demands at a particular base before the j^{th} available spare arrives. But we know that $X - D$ spares will be arriving in $[t, t + T_0]$ and that the last $S - D$ of them will be available. Therefore, we need only compute the probability of no demands at a base before $X - S + j$ out of $X - D$ units arrive. The expected fraction of T_0 for the $X - S + j^{\text{th}}$ event out of $X - D$ uniformly distributed events to occur is $(X - S + j)/(X - D + 1)$. Therefore:

$$1 - p(j) = \exp\left(-\frac{\lambda_d}{N} \cdot \frac{X - S + j}{X - D + 1}\right) \quad (23)$$

where λ_d is the expected number of depot demands in an order and ship time.

We have now developed expressions for $p(D=d, X=x)$ and for $p(j)$ that allow us to evaluate the expression for the probability, L , of a delayed lateral resupply. We can use this to calculate the delayed lateral resupply pipeline, P_L , as:

$$P_L = p(X \geq S) \cdot MT L \quad (24)$$

and the expression for total base backorders now becomes:

$$\sum b_n \approx B + P + P_L \quad (25)$$

AVOIDANCE OF LATERAL RESUPPLY DUE TO UNITS IN TRANSIT FROM THE DEPOT

In some systems, notably that of the USAF, a base is aware of the expected arrival time of units in transit from the depot. If a needed unit is expected to arrive in less than the lateral resupply time, the base does not request a lateral resupply. Our second assumption precluded this case, and we now eliminate that assumption.

Suppose a demand occurs at Base 1. Let l_1 be the number of lateral resupplies in transit to Base 1, x_1 the number of units in resupply for Base 1, and, as before, s_1 the spares level at Base 1. If $x_1 < s_1 + l_1$, there is an available spare at Base 1 to satisfy the demand; no lateral resupply occurs. If $x_1 > s_1 + l_1$, there is an outstanding backorder that is not being satisfied by a lateral resupply, implying that there are no spares available anywhere in the echelon. Thus, a lateral resupply can occur only when $x_1 = s_1 + l_1$, which implies that exactly s_1 units are due in from the depot to Base 1.

Since the lateral resupply time, T , is small compared with the average resupply time, T_r , we can assume that the number of units arriving at Base 1 from the depot in $[0, T]$ is Poisson with mean $\mu = s_1 T / T_r$. Thus, the probability that the lateral resupply is not pre-empted by a spare scheduled to arrive from the depot in less than the lateral resupply time is given by $p(0|\mu)$, where:

$$p(m|\mu) = \frac{\mu^m}{m!} e^{-\mu} \quad (26)$$

Given m arrivals in the time period T , it is known that the expected time to the k^{th} arrival is $Tk/(m+1)$. To modify the base-level backorder total that was computed earlier, we subtract from the lateral resupply pipeline segments those resupplies pre-empted by scheduled arrivals and add back in the time (in backorder status) waiting for the arrival. Let:

$$K_1(T) = \sum_{m=0}^{\infty} p(m|\mu) \frac{1}{m+1} \quad (27)$$

The total base backorder is now given by:

$$\sum b_n = B + P \cdot K_1(T) + P_L \cdot K_1(T) \quad (28)$$

SYSTEMS WITH BASE REPAIR

Suppose now that every base has a repair capability. If the base repair time, T_b , is greater than the lateral resupply time, T , no adjustments in the preceding formulas are needed. However, the average resupply time, T_r , must now reflect the weighted average resupply time to a base, including both depot resupply and base repair times.

If the base repair time is less than T , lateral resupply is pre-empted whenever the customer's carcass is base-repairable. For such components, equation (28) must be modified to reflect this additional pre-empting. For the instantaneous lateral resupply pipeline, P , when the carcass is base-repairable, the K factor is based on a due-in in less than the base repair time instead of the lateral resupply time. For the delayed lateral resupply pipeline, when the carcass is base-repairable, we assume that the entire delayed lateral resupply pipeline is avoided. Therefore, the equation for total base backorders becomes:

$$\sum b_n = B + (1-r)[P \cdot K_1(T)] + r \left[P \cdot K_1(T_b) \cdot \frac{T_b}{T} \right] + (1-r) \cdot P_L \cdot K_1(T) \quad (29)$$

where,

T_b is the base repair time

r is the percentage of carcasses that are base-repairable.

CONCLUSIONS

The model we have described predicts the total number of expected backorders at the bases in a two-echelon resupply system with lateral resupply between the bases. It is based on assumptions of uniform bases and demand processes. Both of these assumptions can be relaxed.

The impact of the uniform base assumption is similar to the impact of that assumption on a traditional METRIC model. An approximative correction factor, similar to that used in some METRIC models, could be used to apply this model to a nonuniform base case.

The model can be modified for the nonstationary case as METRIC can. That is, the pipelines must be computed by integrating functions over time instead of simply multiplying means together.

By repeating the mathematics, we can extend the model to three or more echelons. Any cluster of sites that practice lateral resupply will be modeled separately.

We expect that this model will prove most useful in a nonstationary form, portraying a war-time environment. It is in such a demanding environment that adequate end item support cannot be achieved without exceptional actions, such as lateral resupply, cannibalization, expedited repairs, and other workarounds. Although also of value in portraying a peacetime environment, we expect the nonstationary form of the model, which we are now developing, to be the most useful.

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<p>We model a multi-echelon (S-1, S) continuous review, resupply system in which inter-site movement of assets within the same echelon (lateral resupply) are permitted. Lateral resupply - the lateral movement of assets within a given supply from one site to another to satisfy supply shortages - is common in large, multi-echelon supply systems. In fiscal year 1985, for example, approximately 8 percent of supply shortages affecting aircraft mission capability in the U.S. Air Force were satisfied by lateral resupply between bases.</p> <p>Existing methods for modeling lateral resupply are not practical for use in large-scale models such as the Air Force METRIC (Multi-Echelon Technique for Recoverable Item Control) model. We modify the METRIC approach, which computes total retail expected backorders by item from standard logistics input data (e.g., failure rates and wholesale and retail repair and resupply times), to include incorporation of lateral resupply in the system. Described in terms of a one-item model, our method is specifically designed to provide for efficient processing in a multi-item model.</p> <p>Incorporation of this method in Air Force METRIC-based models can improve evaluation of supply system effects on peacetime readiness and wartime sustainability.</p>			
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